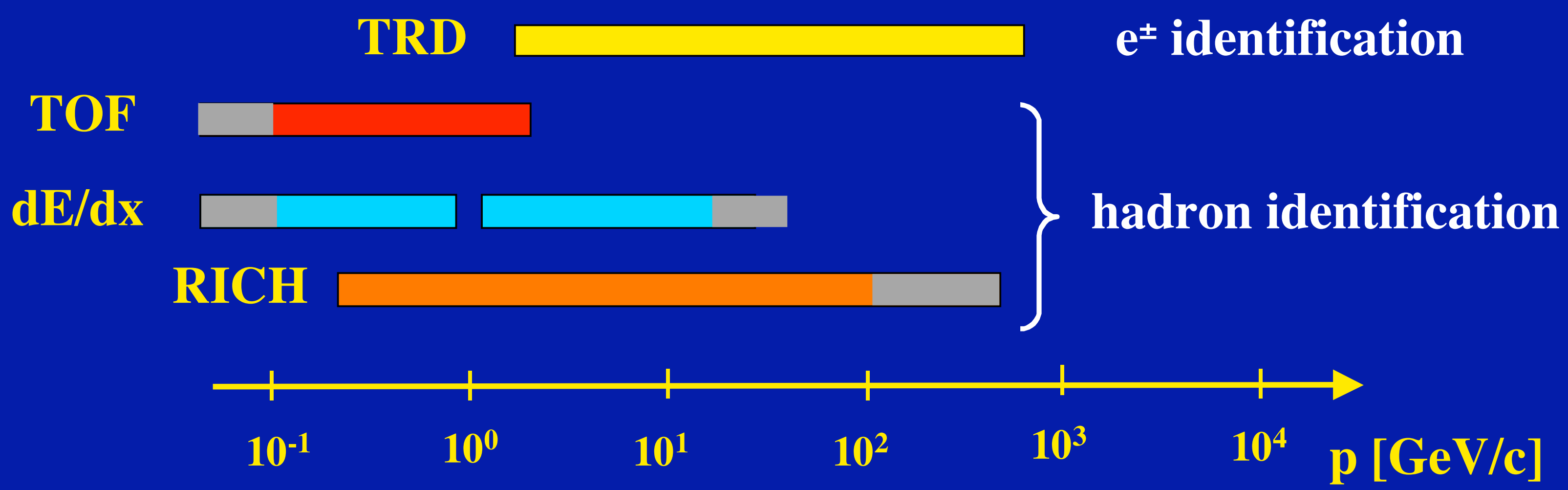
Limits and new directions in PID

J. Va'vra, SLAC

Reach of the present PID techniques



- TOF & dE/dx cover the lowest momentum range.
- TRD is useful for the electron identification at higher momenta.
- RICH technique is clearly superior to all other methods.

Major limit: experimental conditions

LHC ATLAS central region

- Total neutron doses: ~10^{14} /cm^2 after 10 years
- Total charged particle doses : ~10 MRads
- Total charged particle rate : ~10^5 /cm^2 sec
- Total photon rate : ~10^6 /cm^2 sec
- Total neutron rate : ~10^6 /cm^2 sec (~1 m from IP)

SuperB & BelleII:

- L ~ 10^{36} cm^{-2} sec^{-1}

- Total neutron doses: ~10^{12} /cm^2 after 10 years
- Total Gamma doses : ~5x10^{11} /cm^2
- Total charged particle doses : ~5x10^{11} /cm^2
- Bhabha rate per entire detector: ~100 kHz

ALICE Pb + Pb collisions:

- Multiplicity of tracks: ~10,000/event
- Rate: ~50-100 Hz/cm^2

LHC pp diffractive scattering

- L ~ 10^{34} cm^{-2} sec^{-1}

- Total neutron doses: ~10^{12} /cm^2 /year (???)
- Total charged particle doses: ~10^{14} /cm^2/year
- Proton rate in the inner radiator: ~10-15 MHz/cm^2
- Total charge: < 30 C/cm^2/year in worst pixel
- Expected current: < 3.3 μA/cm^2 in worst pixel (from A. Brandt)

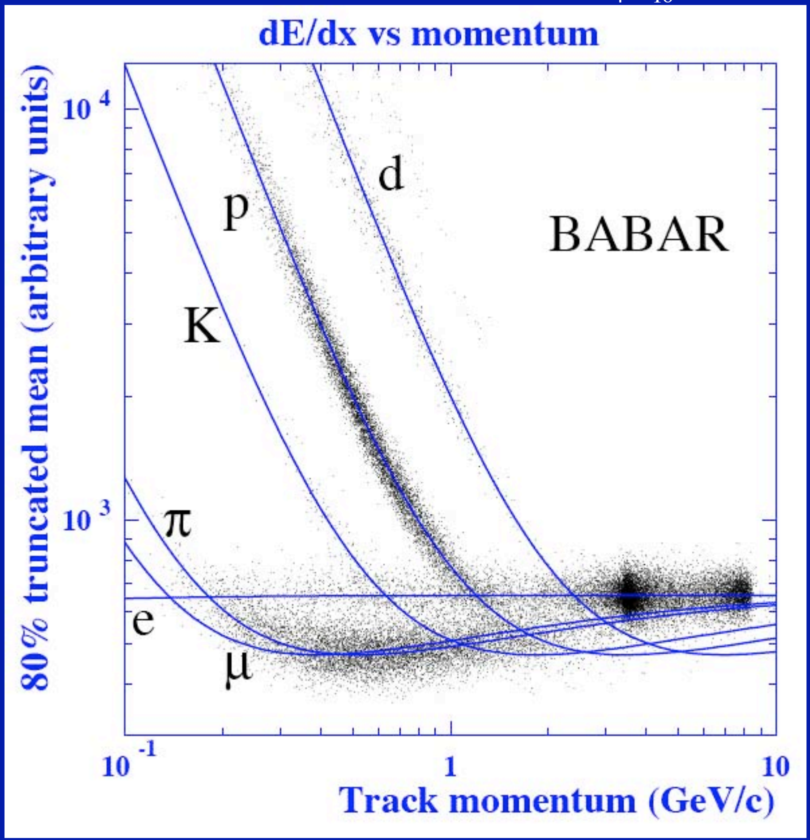
dE/dx

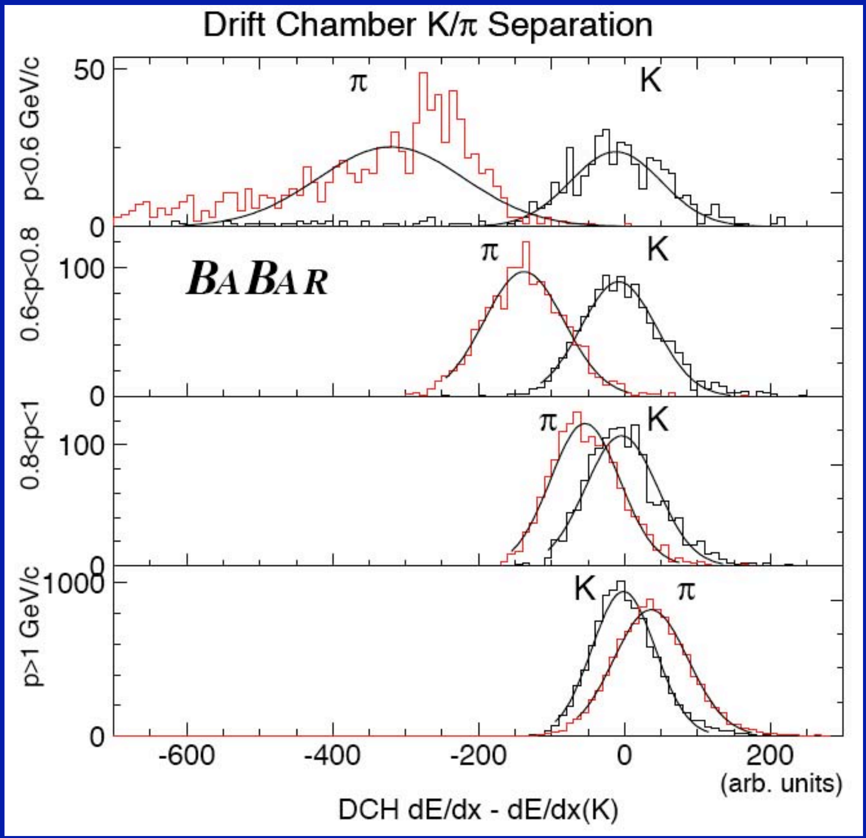
Can we improve the classical dE/dx technique by the cluster counting method ?

BaBar DCH dE/dx performance

M.Kelsey, SuperB workshop, Hawaii, Jan. 2004

n = 30, t = 1.2 cm, 80%He + 20%iC_4H_{10}, 1 bar



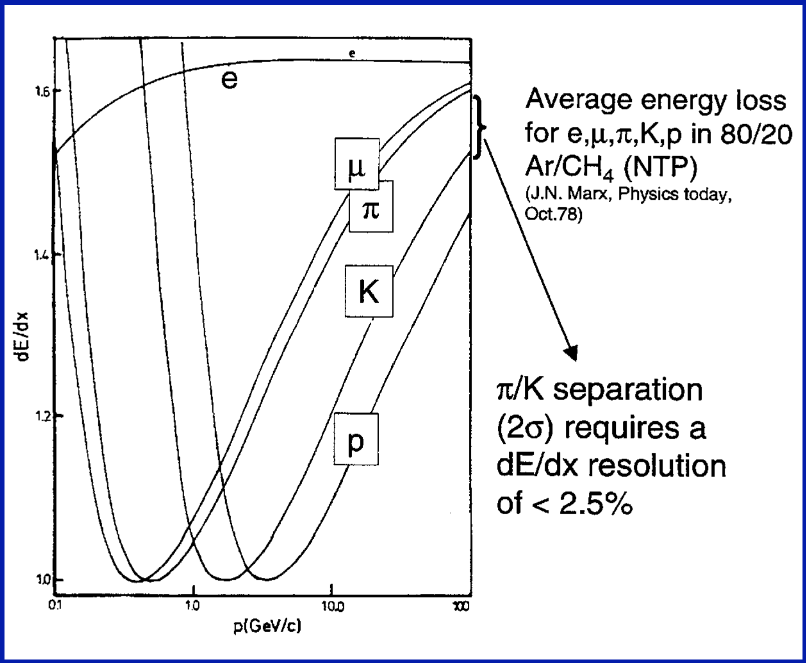


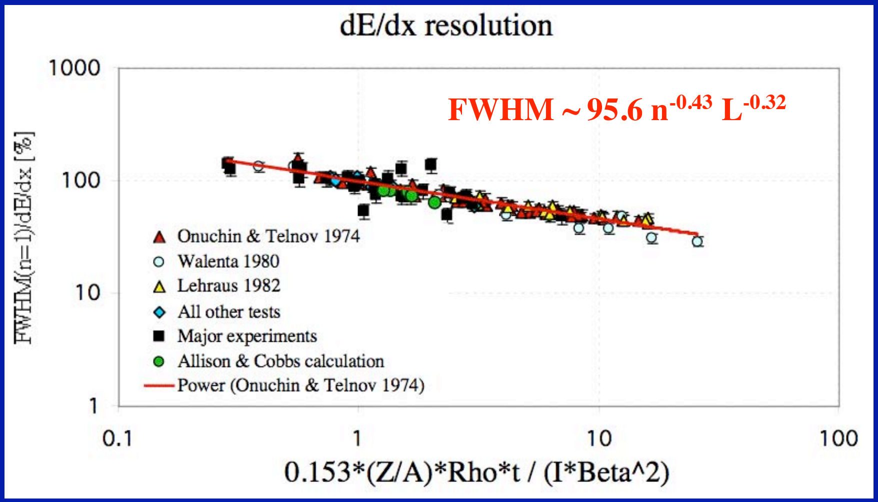
- **A good p/K performance up to ~ 0.7 GeV/c.**
- **Can this be improved by using the cluster counting between 0.7 and 1.5 GeV/c ?**

dE/dx PID technique

$$\boxed{N_\sigma = [dE/dx(m_1) - dE/dx(m_2)] / \sigma(dE/dx)}$$

Bethe-Bloch were first to calculate it in 1930's





Typical dE/dx resolution in typical drift chambers for 1cm in Ar gas at 1 bar:

$FWHM/dE/dx_{\text{most probable}}$ ~ 100%

- **Not much we can do about dE/dx curve.**
- **The only chance is to improve the resolution σ.**

Cluster counting

Original idea to use cluster counting for dE/dx PID by A.Walenta, IEEE NS-26, 73(1979),
others studies: Lapique, F. Piuz, A. Breskin's group, etc. - all doing it with a Time-Expansion-Chamber (TEC).

Use He-based gases:

He: 5.5 ± 0.9 clusters/cm
iC_4H_{10}: 70 ± 12 clusters/cm

G. Cataldi et al., NIM A 386 (1997) 458-469

What do we expect from cluster counting ?

$N_{primary}$ ~ **15**/cm at 1 bar in **95%He+5%iC_4H_{10} gas**:

FWHM/ $dE/dx_{most\ probable} = 2.35 \sqrt{(N_{primary})}/N_{primary}$ ~60%

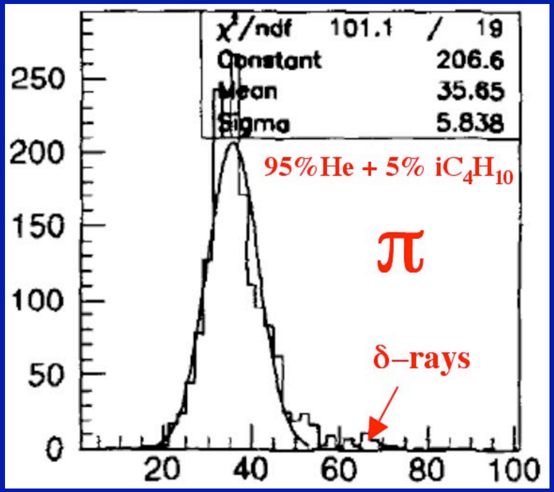
Note: in a SuperB drift cell in the forward direction one expects :
$N_{primary}$ ~ 35/2.6cm-long drift cell => FWHM/(dE/dx) ~$2.35\sqrt{N_{primary\_ions}}/N_{primary\_ions}$ ~ 40%.

- **So far nobody has succeeded to do this in a large experiment.**

KLOE drift chamber R&D

G. Cataldi, F. Grancagnolo, S. Spagnolo, Nucl. Instr.&Meth A 386 (1997) 458-469

Measured cluster distribution in single 2.6cm drift cell:



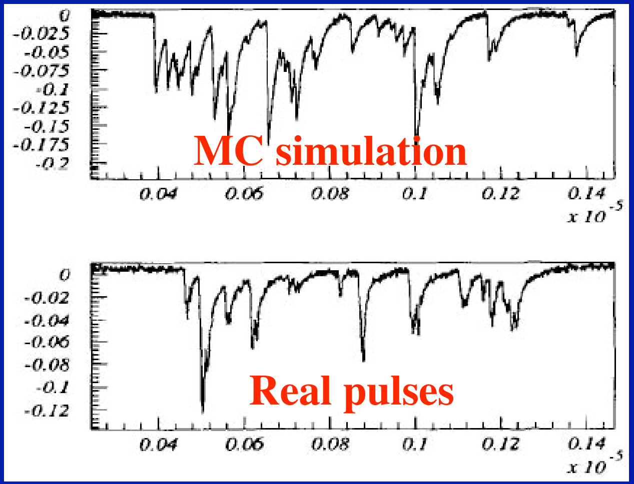
$N_{clusters}$/cell

95%He + 5% iC_4H_{10}

Measure:

~35 clusters/cell

Drift chamber pulses (measured & simulated):



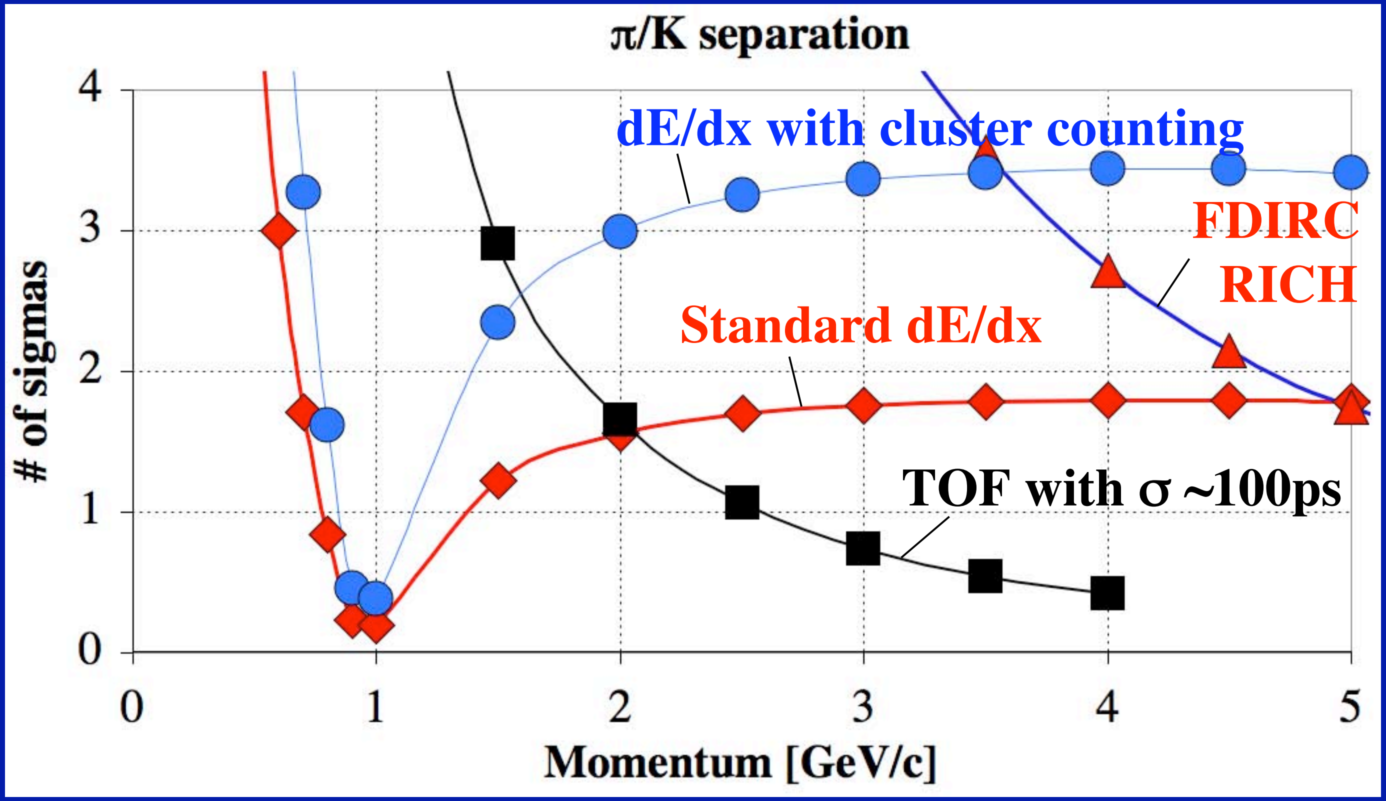
[sec]

- <u>**The conclusion of KLOE R&D:**</u>
  - Preamplifier BW: **~ 500MHz BW**
  - sampling rate: **~1.25 GSa/sec**
  - Memory depth: **~2-3 µsec !!!**
  - ADC dynamical range: **8 bits**

Prediction for SuperB in forward direction

J. Va'vra, RICH 2010, Cassis, France

~1.8 m flight path in forward direction:



- **A combination of the cluster counting plus a "cheap" TOF counter with a ~100ps resolution is good enough solution for the forward PID at SuperB.**

TOF

Can we make a new breakthrough by using new fast detectors ?

Detector candidates:

- Multi-gap glass RPCs ≡ MRPC
- MCP-PMTs
- G-APDs

(**Other names:** SiPM, SiPMT, MGPD, MRS-APD, PSiPs, SPM, MPPC, …)

TOF PID technique

Principle is simple:

$$\Delta t = (L_{path}/c) * (1/\beta_1 - 1/\beta_2) = (L_{path}/c) * [\sqrt{(1+(m_1 c/p)^2)} - \sqrt{(1+(m_2 c/p)^2}] =$$

$$\sim (L_{path} c/2p^2) * (m_1^2 - m_2^2)$$

Therefore expected particle separation: $\boxed{N_\sigma = [(L_{path} c/2p^2) * (m_1^2 - m_2^2)] / \sigma_{Total}}$

Example of contributions to the timing resolution:

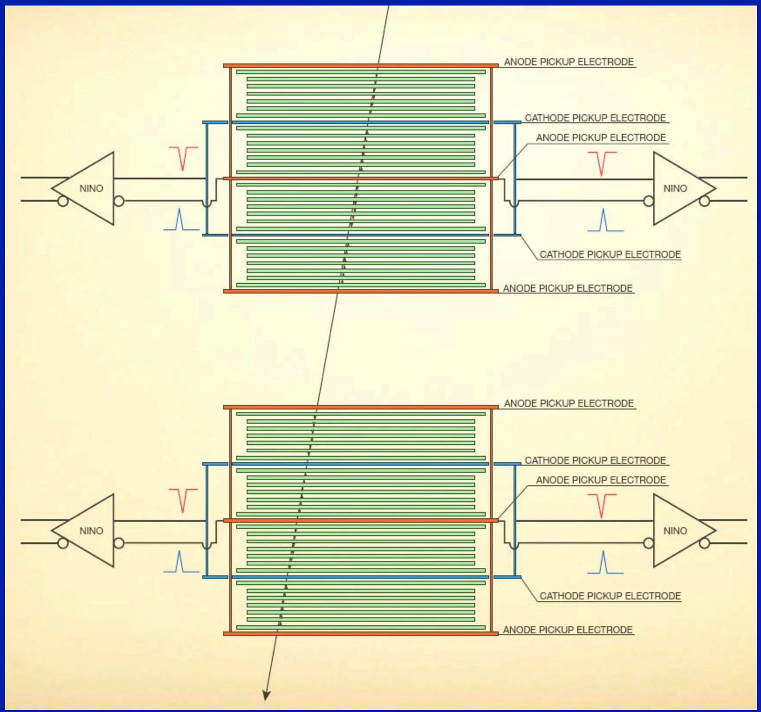
$$\sigma_{Total} \sim \sqrt{[(\sigma_{TTS}/\sqrt{N_{pe}})^2 + (\sigma_{Chromatic}/\sqrt{N_{pe}})^2 + \sigma^2_{Electronics} + \sigma^2_{Track} + \sigma^2_{T0}]}$$

$\sigma_{Electronics}$ - electronics contribution
$\sigma_{Chromatic}$ - chromatic term = f (photon path length)
σ_{TTS} - transit time spread
σ_{Track} - timing error due to track length L_{path}
σ_{T0} - start time (In SuperB or Belle II machines it is dominated by the bunch length to >20ps)
etc.

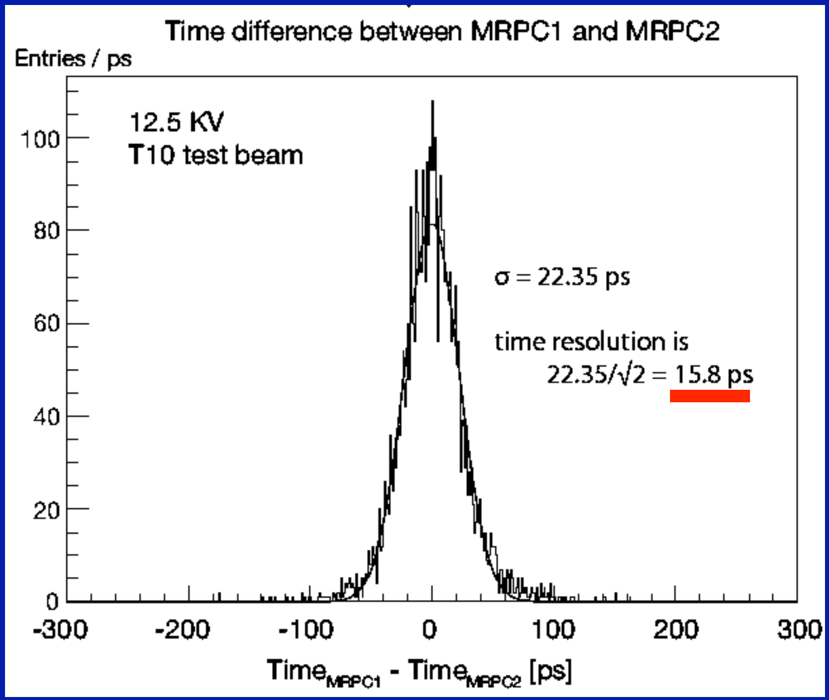
New R&D effort: 24 MRPC gaps

C. Williams, talk in Orsay, 2009 and private discussion at CERN, 2010.

24-gaps/MRPC:



Test beam results: resolution per single MRPC

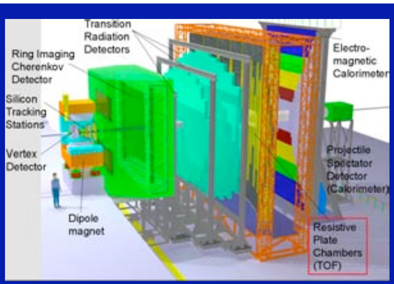


- **24 active gaps/MRPC**
- **Gap size: 160 µm**
- **~ 14% of r.l.**
- **Pad readout**
- **Max. possible rate ≤ 1 kHz/cm²**

Idea of this detector:

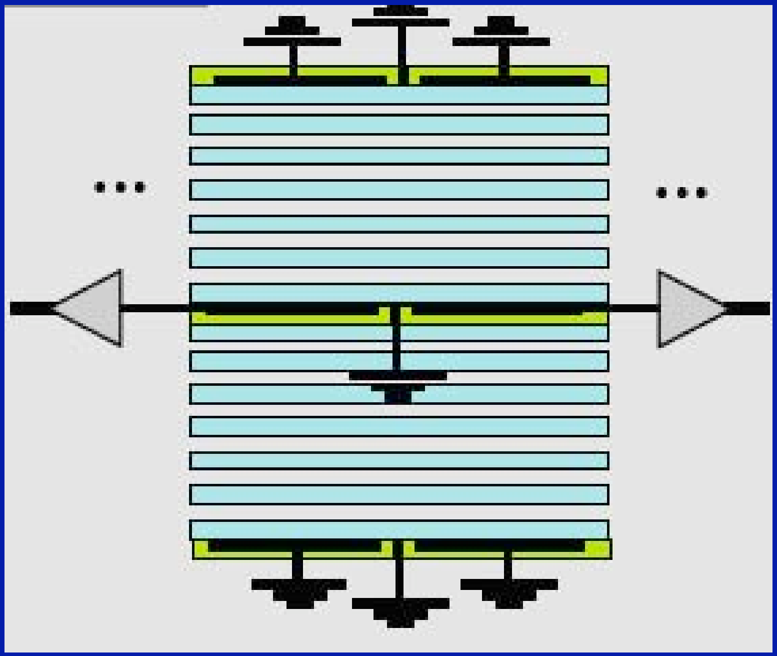
- High gain operation.
- To prevent sparking make very tiny gaps to stop avalanche growth.
- Electron has to be produced very near cathode to get a large enough signal.
- To get a high overall efficiency one needs many gaps.
- C.Williams thinks that the limit is ~10ps.

CBM experiment at FAIR

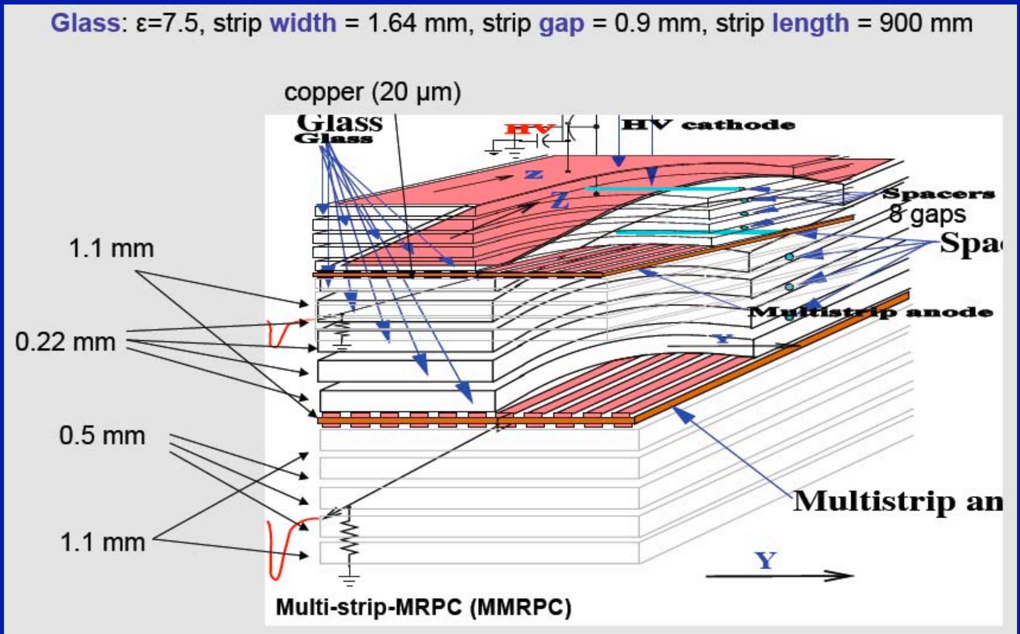


CBM MRPCs, http://cbm-wiki.gsi.de/cgi-bin/view/Public/PublicTof.

12-gap design:



Strip-line design :

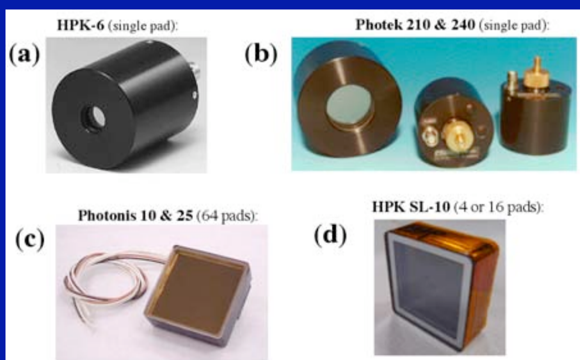


- **They are developing MRPCs with multiple strip-line readout to reduce the channel count.**

TTS timing resolution obtained in the present commercial MCP-PMTs

J. Va'vra, RICH 2010, Cassis, France

Present commercially available MCP-PMT detectors:



MCP-PMT	# of anodes	MCP size	Hole [μm]	QE [%]	Photocathode	TTS [ps]	Risetime [ps]
HPK-6	1	ϕ11mm	6	26	Multi-alkali	~11 [+]	< 150 [+]
HPK-10	1	ϕ25mm	10	26	Multi-alkali	< 35 [a]	< 200
HPK SL-10	4	22x22	10	24	Multi-alkali	< 30 [a], < 32 [c]	< 200 [a]
BINP-6	1	ϕ18mm	6	18	Multi-alkali	< 27 [c]	< 200
Photonis-10	64	49x49	10	24	Bi-alkali	< 30 [b], < 32 [f]	< 400 [f]
Photonis-25	64	49x49	25	24	Bi-alkali	< 40 [e], < 40 [f], < 37 [c]	< 400 [f]
Photek-210	1	ϕ10mm	3.2	30	Multi-alkali	< 33 [d], < 16 [f], < 14 [*]	~81 *
Photek-240	1	40mm	10	30	Multi-alkali	< 40-45 [d]	~180 *

Hamamastu data[+], K. Inami [a], J. Va'vra[b], A. Lehman[c], A.Rozhnin[d], S. Korpar[e], A. Brandt[f]

- **Major present questions/limitations:**

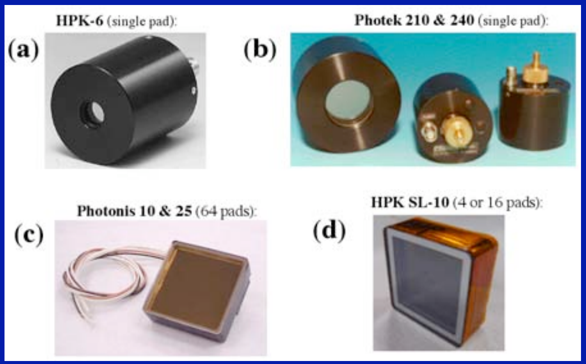
  - cost, aging, rate limitation, difficulty to get tubes with 10μm pores, geometrical limitations, systematics of the setup, cross-talk, electronics

Timing resolution obtained in the beam with quartz radiator

J. Va'vra, RICH 2010, Cassis, France

- **Quartz radiator**
- **Both a radiator and the MCP-PMT located in the beam (entering perpendicularly to MCP face)**

Present commercially available MCP-PMT detectors:



MCP-PMT	# of anodes	Gain	Hole dia. [μm]	Window thickness [mm]	Radiator length [mm]	Npe	Resolution [ps]
HPK-6	1	$\sim 10^6$	6	3	10	~ 80	**~ 6.2 [a]**
Photonis-10	64	$\sim 2\times10^4$	10	2	10	~ 35	**~ 14.0 [b]**
Photonis-25	64	$\sim 10^6$	25	2	6	~30	**~ 13.9 [b]**
Photek-240	1	$\sim 10^6$	10	9.6	0	70-80	**~ 7.7 [c]**
Photek-210	1	$\sim 10^6$	3.2	5.6	0	45-50	**~ 12 [c]**
Photonis-25	64	$\sim 10^6$	25	2	0	~15	**~ 37 [d]**

K. Inami et al. [a], J. Va'vra et al.[b], A.Rozhnin et al.[c], S. Korpar et al.[d]

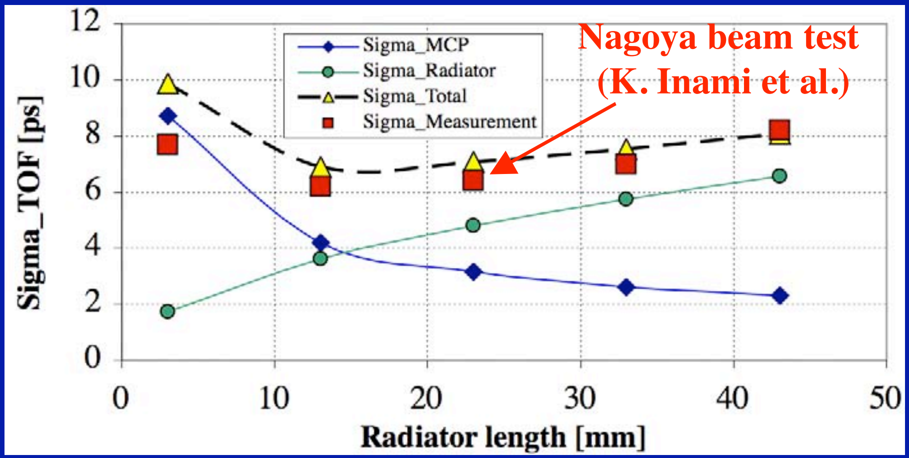
- **Major questions/limitations when using these detectors on a large scale:**

- cost, aging, rate limitation, difficulty to get tubes with 10μm pores, geometrical limitations, systematics of the setup, cross-talk, electronics

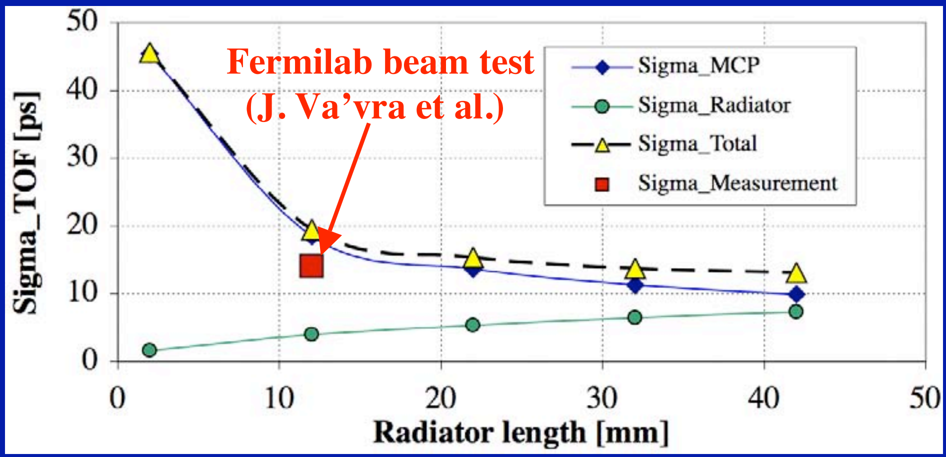
High gain vs. low gain operation

J. Va'vra, RICH 2010, Cassis, France

High gain operation:



Low gain operation:



To get a good timing one needs a total charge of at least 6-8x10^5 electrons:

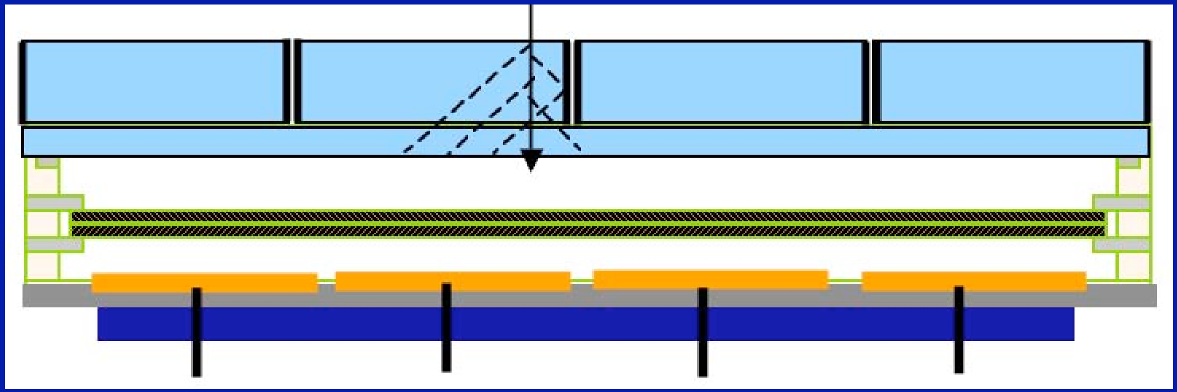
1) **High gain (operation sensitive to a single pe):**
- One can use even 3 mm thick radiator, and still get a good result.

2) **Low gain (operation is not sensitive to a single pe):**
- Motivated by rate and aging problems at SuperB factory due to a large single photoelectron background.
- Main disadvantage of this approach is that the resolution degrades very rapidly as Npe goes down for shorter radiator length. One needs at least 10 mm radiator length plus 2 mm window thickness to get a good resolution at low gain.

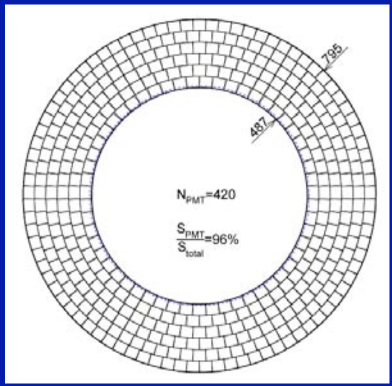
Too soon to think about a pixilated TOF ?

J. Va'vra, RICH 2010, Cassis, France

SuperB-related using the Planacon MCP-PMT:



Forward TOF:



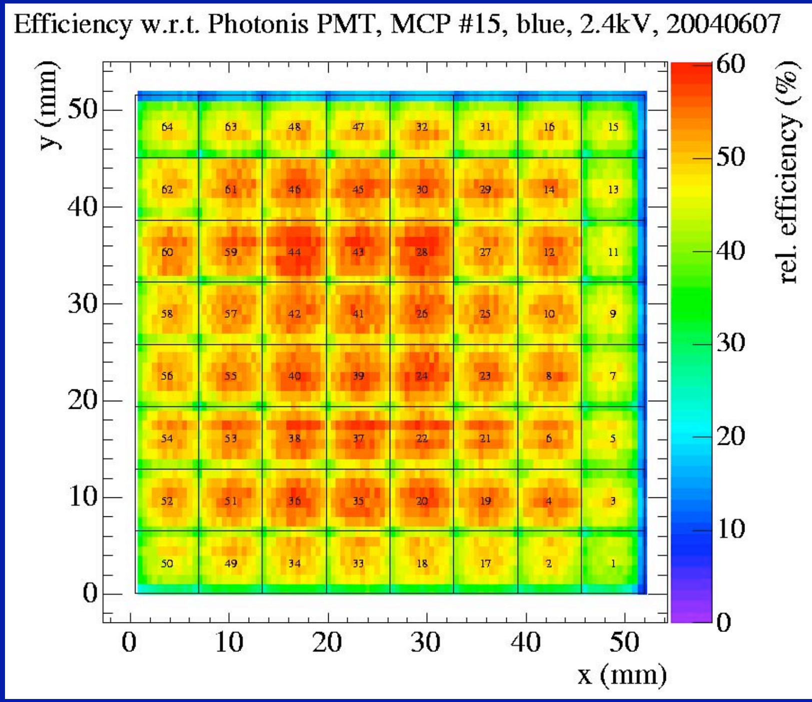
Would need ~550

- **Low enough gain (2-3 x 10^4) to be insensitive to single photoelectron background, i.e., detect only <u>charged tracks</u>.**
- **Fused silica radiator thick enough to produce N_{total} ~ 6-8 x 10^5 electrons/track to get a sufficient S/N ratio for good timing.**
- **This detector, unfortunately, will not happen at SuperB as these MCP-PMTs are too expensive at present.**

MCP-PMT Relative efficiency to Photonis XP2262B

C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, and J. Va'vra, Nucl.Instr. & Meth., A553(2005)96-106

Planacon with 25μm holes:

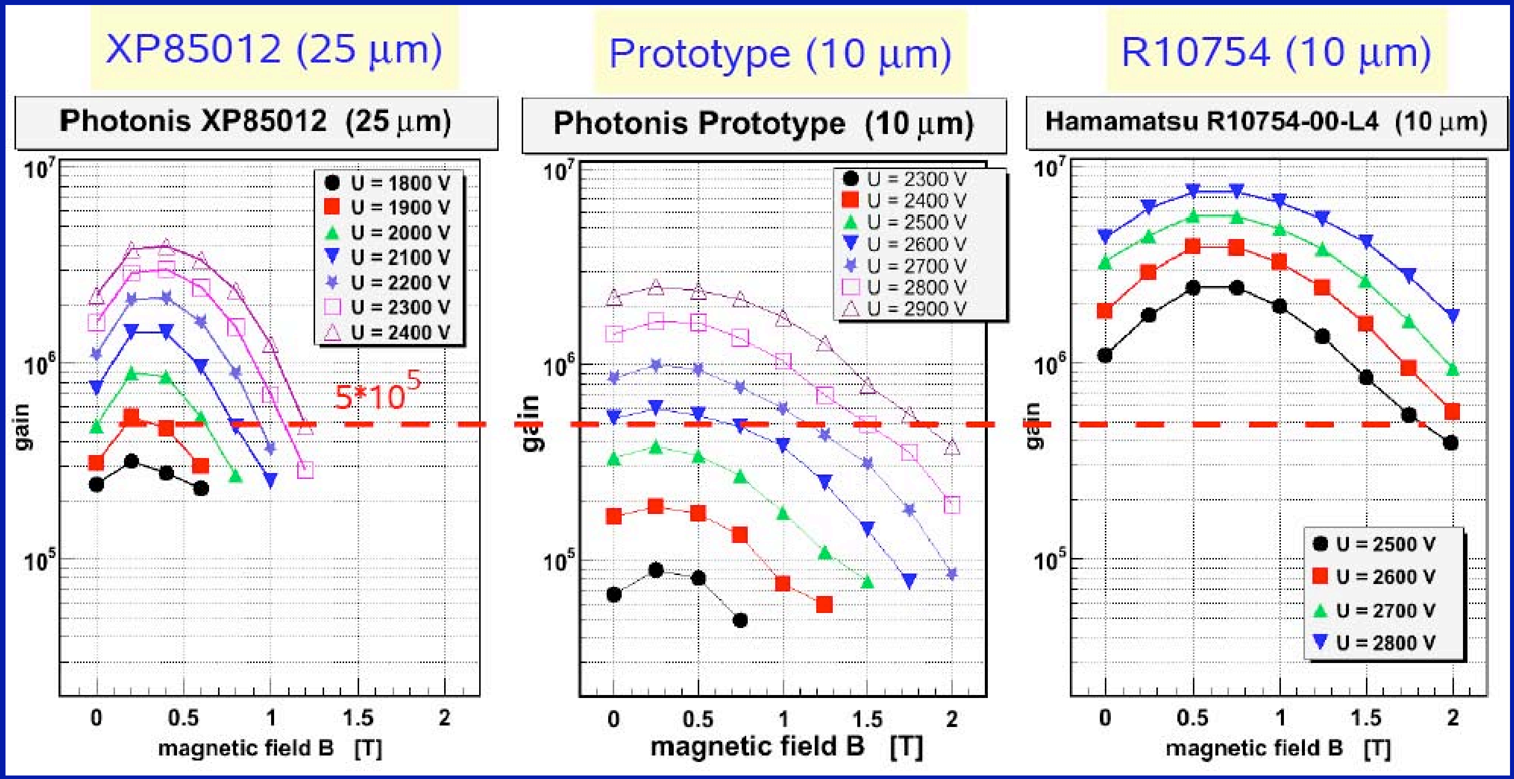


- **Relative photon detection efficiency (PDE) to 2" dia. Photonis XP2262/B is only < 50%, if one takes into account only in-time hits.**

MCP-PMT: Gain = f(magnetic field)

A. Lehman, RICH 2010, Cassis, France

Panda magnetic field: 2T

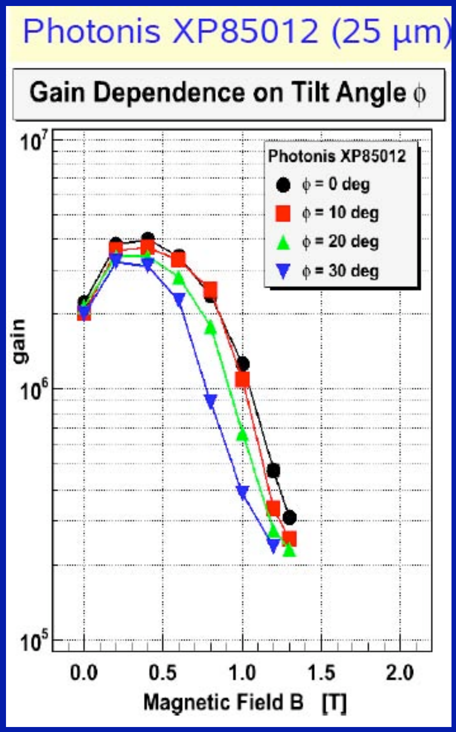


- **25µm tube perhaps good enough up to 1T.**
- **Photonis 10µm tube might work at 2T, if you are willing to then at a maximum voltage, which may not be smart thing to do in a large system.**
- **Hamamatsu R10754 tube may work at 2T.**

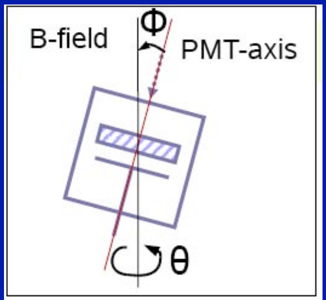
MCP-PMT: sensitivity to angles

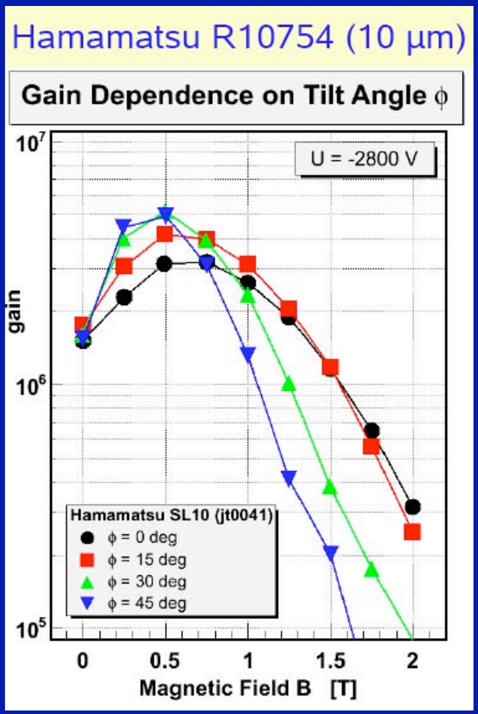
A. Lehman, RICH 2010, Cassis, France

Photonis MCP-PMT:



Hamamatsu MCP-PMT:



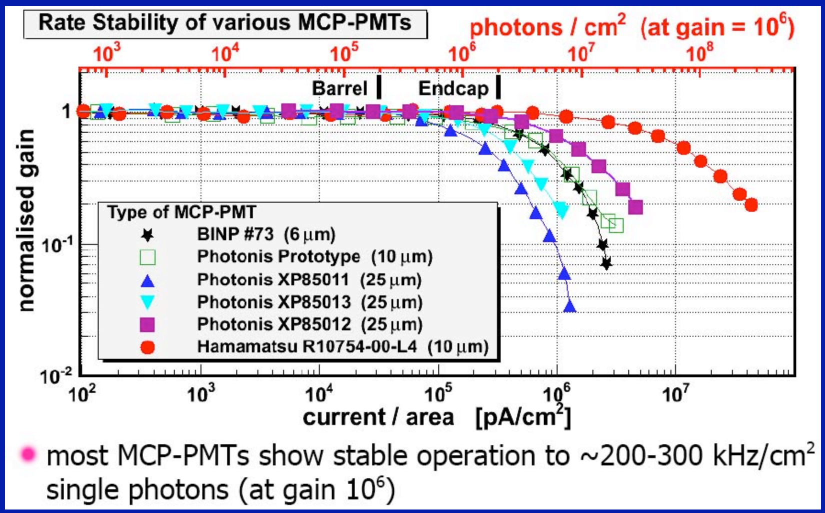


- **A significant loss of gain at high B-field and for large angles.**

MCP-PMT: Rate and aging limitations

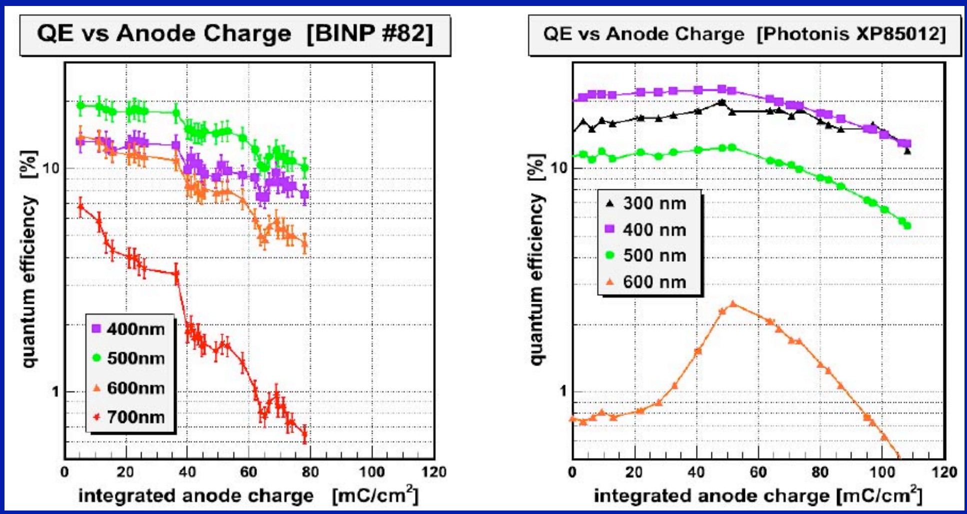
A. Lehman, RICH 2010, Cassis, France

Rate capability:



(PANDA R&D, no magnetic field)

QE aging:

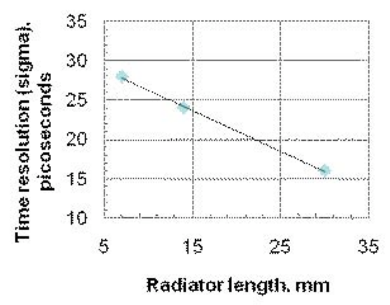


- **MCP-PMTs seem to be able to handle 200-300 kHz/cm^2 at a gain of 10^6.**
- **Photocathode aging is a wavelength dependent.**

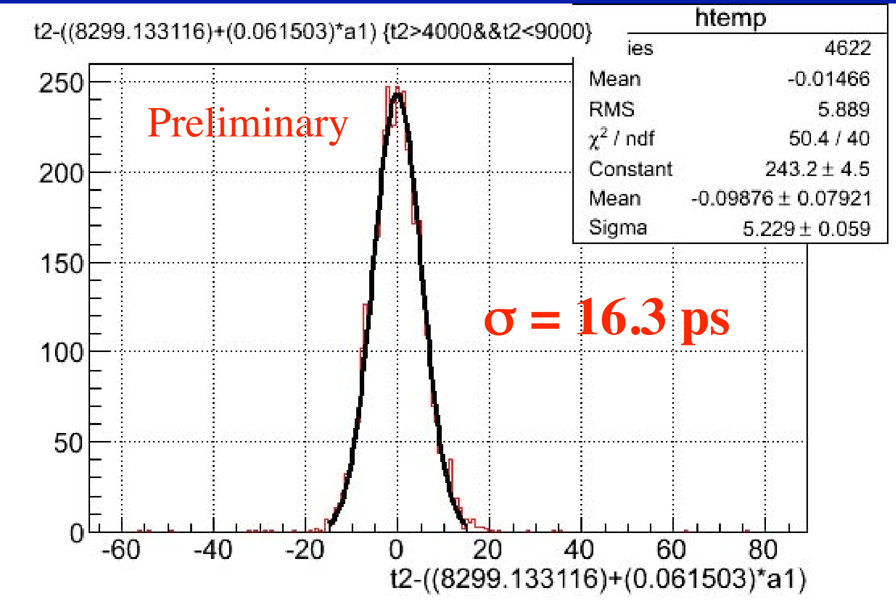
Beam tests with G-APD in Fermilab

A. Ronzhin, M. G. Albrow, M. Demarteau, S. Los, S. Malik, A. Pronko, E. Ramberg, A. Zatserklyaniy, Fermilab

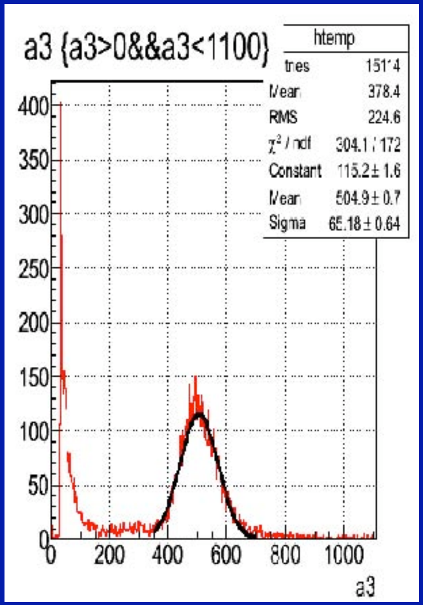
Single 3x3mm^2 G-APD with 3cm-long quartz radiator:



Fused Silica radiator: 3x3mm^2, 3cm long



Npe ~ 60 pe's

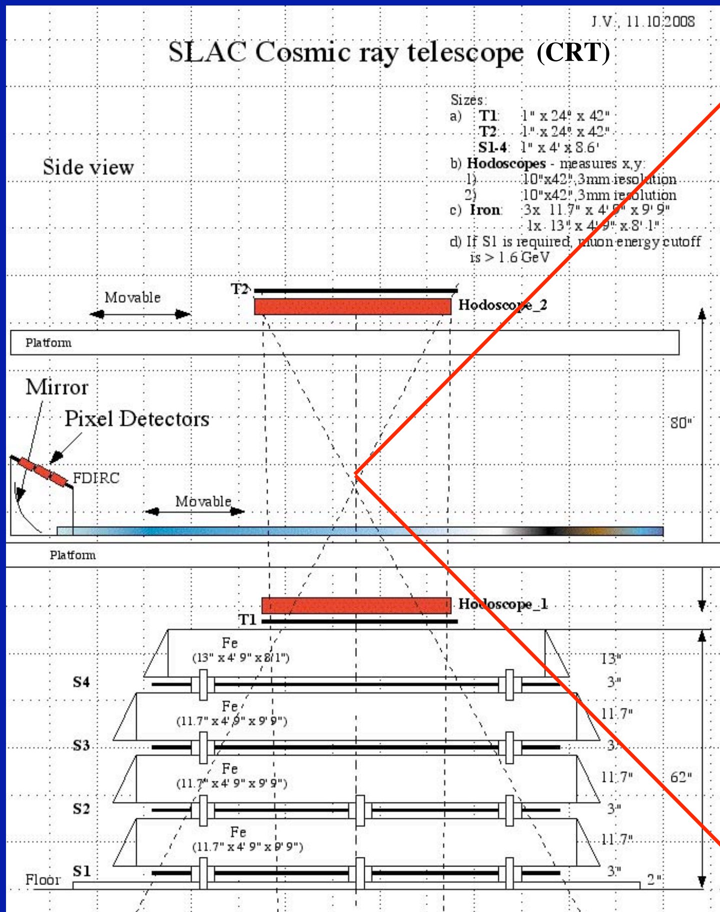


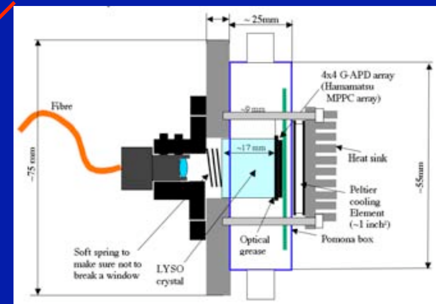
- **<u>Timing start</u>: G-APD (Hamamatsu MPPC, radiator is fused silica, 3x3 mm^2 and 30 mm long, all surfaces polished)**

  <u>Timing stop</u>: Photek 240 (radiator is the MCP window, 9.6 mm thick).
- **The MPPC time resolution is <15 ps assuming the Photek 240 time resolution is 7.7 ps. Small pulse height cuts and slewing correction applied.**
- **120 GeV protons used for the test. Normal incidence.**
- **<u>Attention has to be paid to ΔT & ΔV stability</u>: 11.5ps/0.5^{o}C & 6.2ps/10mV !!**

Simple pixilated TOF counter with σ ~ 100ps

J. Va'vra (test & analysis), K. Nishimura (DAQ issues), A. Rozhnin (provided 4x4 SiPMT array), S. Los (PC-board)





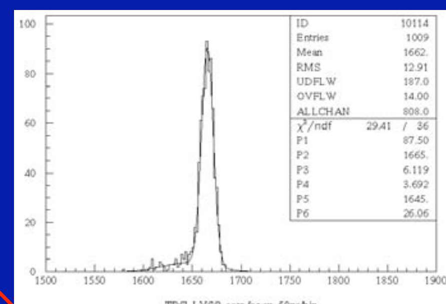
Fiber entry for calibration

1.7cm^3 **LYSO + G-APD**

4x4 G-APD array

(running @ 70.9 V)

(G-APD ≡ SiPMT)



$$\sigma \sim \sqrt{\sigma^2_{LYSO} - \sigma^2_{Start}}$$
$$< \sqrt{(152^2 - 76^2)}$$
$$< 132 \text{ ps}$$

Preliminary

- **To obtain these results, one has to use a CRT 3D tracking, ADC corrections, E > 1.5 GeV**
- **SuperB Forward TOF: Can we just glue G-APD array to LYSO crystals from the front ?**
- **The only problem: the cost of 4 x 4 G-APD array is too high at the moment ($3.5k/piece)**

Today I got this e-mail from Hamamatsu

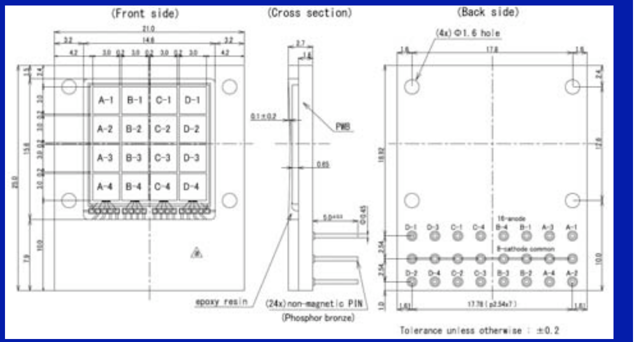
Hi Jerry,

we are planning to release a monolithic version of the 4x4 MPPC. The pricing should come down drastically because it is a solid state device and price scales with volumes. The PET/MRI industry is very interested in purchasing a high volume of these detectors.

I believe that at the 5000 piece price we will be either very close to being a factor of 10 less expensive. For example I looked at some current quotes. The S11064 at one piece is roughly $3100 (with academic discount). It drops down to roughly $1250 a piece at 100 pieces and down to $650 at 1000 pieces. **Therefore, the "5k pieces" price will be very close to your target price of $350.00 per piece.** Please let me know if you need an official quote. I have also attached a drawing of our new monolithic 4x4 MPPC device. Feel free to let me know if you have any questions.

Best Regards, William

4x4 G-APD monolithic array:



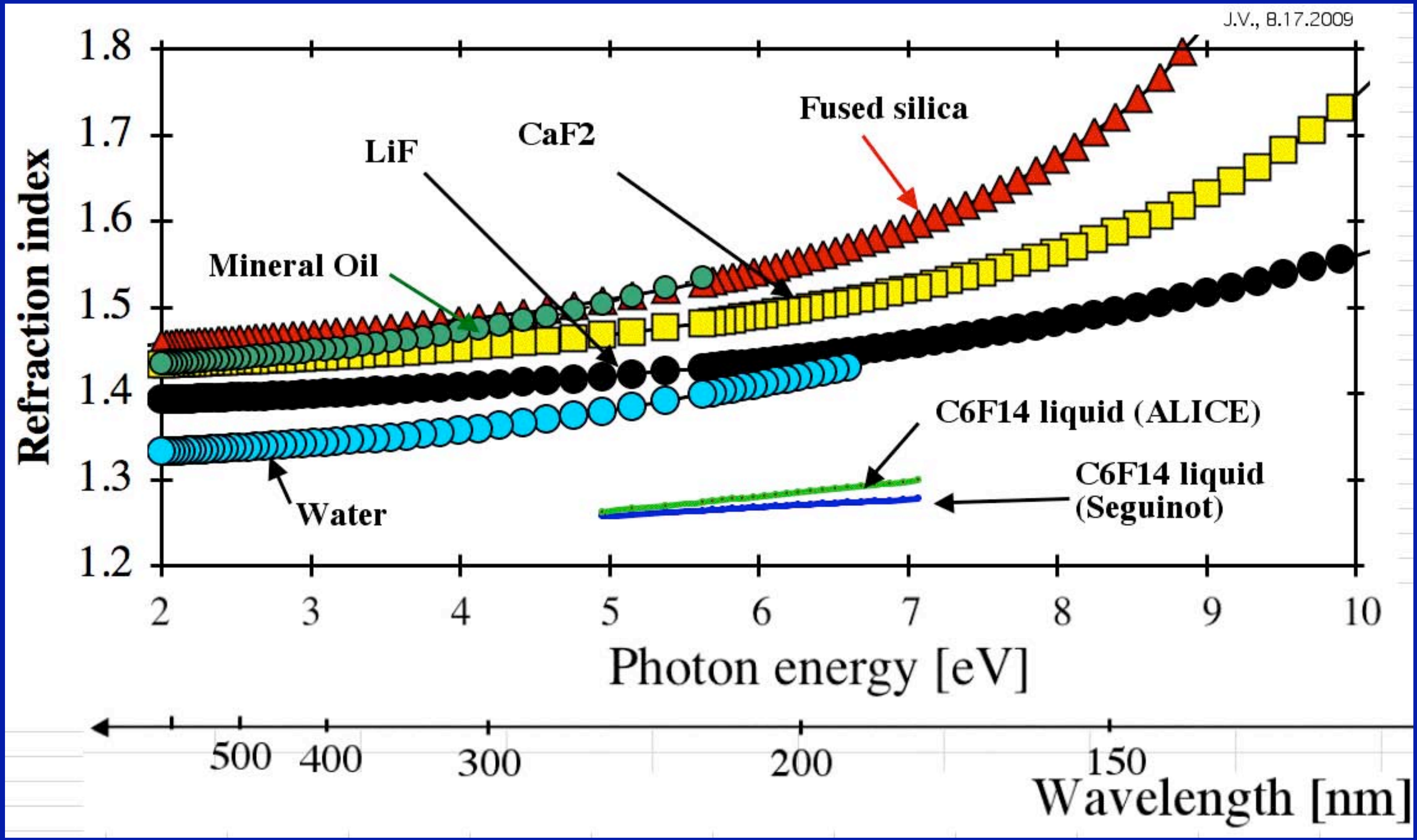
Cherenkov detectors

DIRC-like RICH detectors are blooming

Refraction index

J. Va'vra, The 42-nd workshop on Supercolliders, Erice, Sicily, Italy, 2003, SLAC-PUB-11019

$E \sim 1/\lambda$



- The Cherenkov light theory can be described by only one constant: n = n(E).
- It also provides limits: number of photons, chromatic behavior, etc.

Examples of Cherenkov angles and Npe

$$\cos \theta_c = 1 / \beta\, n(\lambda)$$

$$Npe = 370\, L \int \sin^2\theta_c (E)\, \Pi_i \varepsilon_i (E)\, dE \sim L\, N_o \sin^2 \theta_c$$

Npe - number of photoelectrons, L - radiator thickness, ε_i - various detection efficiencies

Radiator type	Refraction index n	θ_c (max) ($\beta = 1$)	$\Delta\theta_c = \theta_c(\pi) - \theta_c(K)$ [mrad]	Npe / cm (No = 50 & $\beta = 1$)
Aerogel (SiO_2)	1.05	309 mrad	22.8 @ 4 GeV/c	4.6
Solid Quartz (SiO_2)	1.47	823 mrad	6.5 @ 4 GeV/c	27
H_2O	1.34	728 mrad	7.9 @ 4 GeV/c	22
C_5F_{12} gas at 1 bar	1.0017	58.3 mrad	2.6 @ 10 GeV/c	0.17
He gas at 1 bar	1.00004	8.9 mrad	1.4 @ 100 GeV/c	0.004

- **N_o is a measure of quality of the optical system and a detector performance.**
- **$N_o \sim 20$ -100 cm^{-1} typically.**
- **N_o is limited mainly by photon detection efficiency (PDE), which is typically 10-20%.**

Threshold Cherenkov counters

T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)30-51

Detectors measure Npe, but not θ_c angle

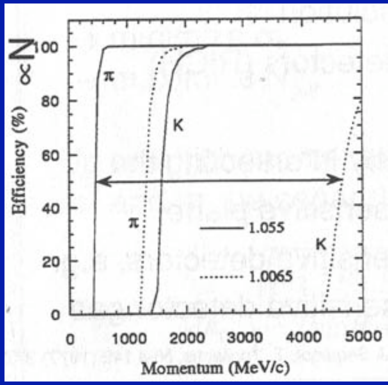
For a given n, a particle of mass m will produce light if: $\boxed{p > p_{thr} \sim m/\sqrt{(n^2-1)}}$

<u>The threshold counter scaling:</u>

$$\boxed{(\sigma_\beta/\beta)_{thr} = \tan^2\theta_c/(2\sqrt{Npe})}$$

Example how a threshold counter: Two aerogel radiators, R_1 and R_2, with $n_1 = 1.055$ and $n_2 = 1.0065$

Example of threshold counter is **Belle Aerogel Detector:**



for $p > 0.4$ GeV/c: detect π in R_1

$p > 1.2$ GeV/c: detect π in R_1 & R_2

$p > 1.4$ GeV/c: detect K in R_1

$p > 4.2$ GeV/c: detect K in R_1 & R_2

=> p/K separation between 0.4 and 4.3 GeV/c

Note: The threshold counters are sensitive to background near the threshold

RICH ≡ Ring Imaging Cherenkov counters

T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)1-29 and
T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)30-51

Detectors measure $\theta_c = \arccos(1/n\beta)$

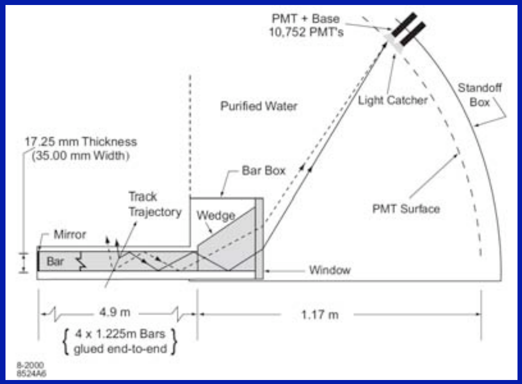
The scaling of RICH counters:

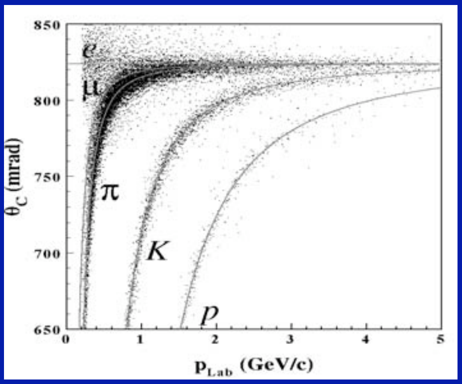
$$(\sigma_\beta/\beta)_{RICH} = \sigma_{\theta c}(tot) * \tan\theta_c \sim [\sigma_{\theta c}(\text{single pe})/\sqrt{Npe}] * \tan\theta_c$$

$$=> (\sigma_\beta/\beta)_{thr} / (\sigma_\beta/\beta)_{RICH} = \tan\theta_c/(2\,\sigma_{\theta c}(tot)) > 200 \text{ for DIRC-like RICH}$$

RICH detectors are much more powerful PID instruments than the threshold detectors.

Example of RICH imaging:
(BaBar DIRC)
I. Adam et al., The DIRC PID for BaBar, Nucl. Instr. & Meth. A538(2005)281-357
DIRC = Detection of Internaly Reflected Cherenkov (Light)





Resolution of RICH detectors: $\sigma_{\theta c}$(tot)

B. Ratcliff, Trieste RICH conference, 2008, Nucl. Instr. & Meth. A595(2000)1-7

$$\boxed{\sigma_{\theta c}(\text{tot}) \sim \sigma_{\theta c}(\text{single photoelectron}) / \sqrt{N_{pe}} \oplus \sigma_{\theta c}(\text{track systematics})}$$

$$\sigma_{\theta c}(\text{single photoelectron}) = \sqrt{[\sigma_{\theta c}^2(\text{chromatic}) + \sigma_{\theta c}^2(\text{pixel}) + \sigma_{\theta c}^2(\text{imaging}) + \sigma_{\theta c}^2(\text{transport})\ldots]}$$

$$\sigma_{\theta c}(\text{track systematics}) \sim \sqrt{[\sigma_{\theta c}^2(\text{external tracking}) + \sigma_{\theta c}^2(\text{multiple scatt.}) + \sigma_{\theta c}^2(\text{alignment errors})]}$$

where

N_{pe} - number of photoelectrons detected in a wavelength bandwidth $\Delta\lambda$
$\sigma_{\theta c}$(chromatic) - resolution broadening because of color dispersion: $n = n(\lambda)$
$\sigma_{\theta c}$(pixel) - broadening due to finite detector pixel size
$\sigma_{\theta c}$(imaging) - effect of the imaging method (lens, mirrors, etc.)
$\sigma_{\theta c}$(transport) - applicable only to DIRC-like counters (otherwise negligible)

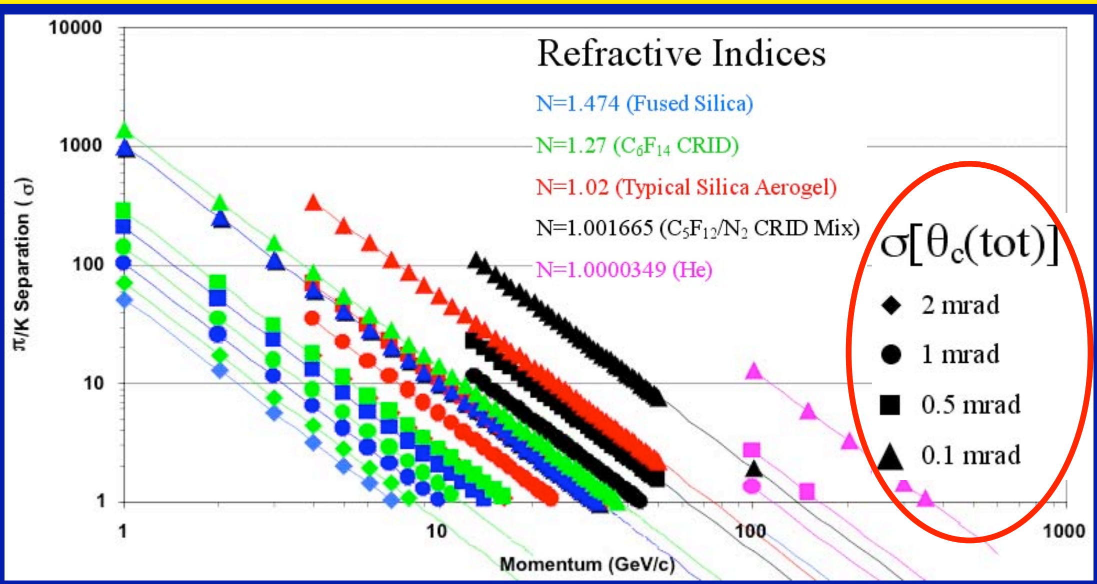
- **To get smallest possible $\sigma_{\theta c}$(tot), one should maximize N_{pe} and minimize all error contributions.**
- **In practical counters $\sigma_{\theta c}$(tot) is typically between 0.1 and 2 mrads.**

“Ideal” PID separation

T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)30-51 and
B. Ratcliff, Trieste RICH conference, 2008, Nucl. Instr. & Meth. A595(2000)1-7

$N_\sigma = [\ \theta_c(m_1) - \theta_c(m_2)\ ] / \sigma_{\theta c}(\mathrm{tot})$ - separation in number of sigmas

$\sim (m_1^2 - m_2^2) / [\ 2p^2\, \sigma_{\theta c}(\mathrm{tot}) \sqrt{(n^2-1)}\ ]$ **for a limiting case of $\beta = 1$**

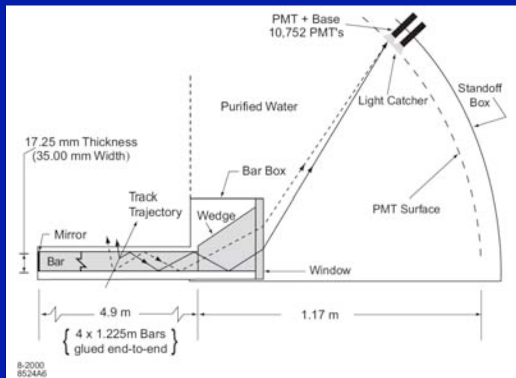


- **In practical counters $\sigma_{\theta c}(\mathrm{tot})$ is typically between 0.1 and 2 mrads.**
- **Refraction index n choice:**
  - **<u>low index</u> is required for a <u>high momentum range</u>. Counters become very long in order to get a large enough Npe.**
  - **<u>high index</u> is required for a <u>low momentum range</u>**

BaBar DIRC ---> SuperB FDIRC

J. Va'vra, D. Roberts and B. Ratcliff, RICH 2010, Cassis, France

BaBar DIRC



DIRC proved to be a very reliable detector at BaBar.

3D imaging (x, y & time):

(a) ~11,000 x-y points

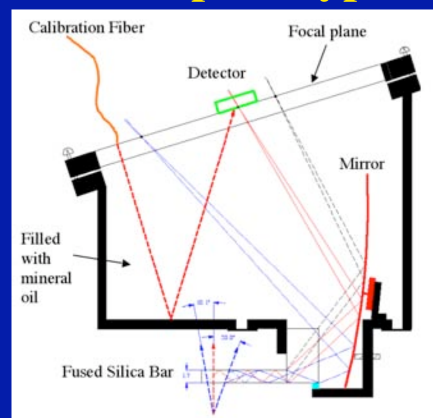
(b) time window : ± 8ns

(σ ~1.7ns /photon)

$\sigma_{\theta c}$ ~ 9.6 mrads/photon

100x higher luminosity

FDIRC prototype



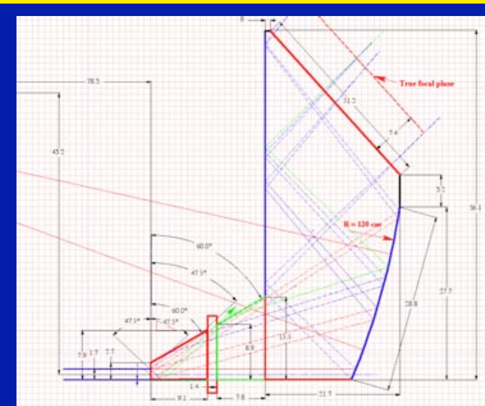
Prototype verified the focusing concept using pixilated photon detectors. **<u>The very first RICH detector establishing that the chromatic error can be corrected by timing ! At this point nobody else did it !!!</u>**

FDIRC design for SuperB

(a) ~18,432 x-y points

(b) time window : ± 1-2ns

(σ =200ps /photon)

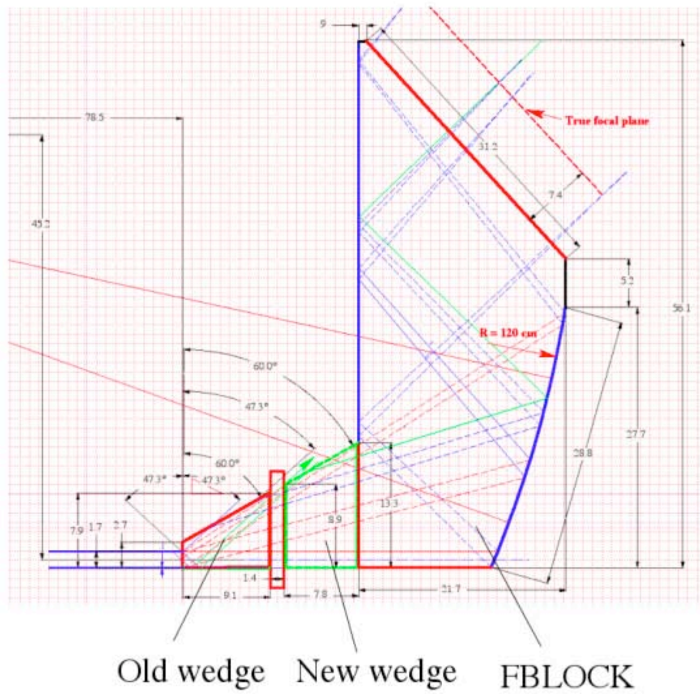


3D imaging (x, y & time),
<u>25x smaller volume and</u>
<u>10x faster than BaBar DIRC</u>
$\sigma_{\theta c}$ ~ 9.6 mrads/photon

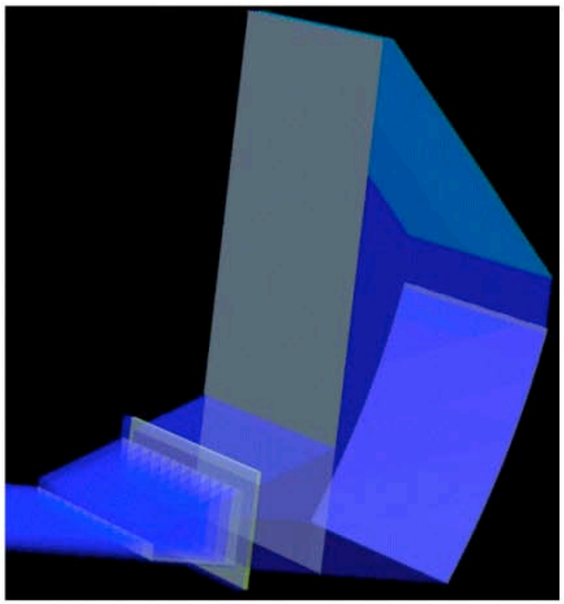
Ray tracing & MC simulation

J. Va'vra, Ray tracing design plus a simulation with Mathematica, SLAC-PUB-13464 & SLAC-PUB-13763,
D. Roberts, "Geant 4 model of FDIRC", SuperB meeting, Annecy, Oct. 2009

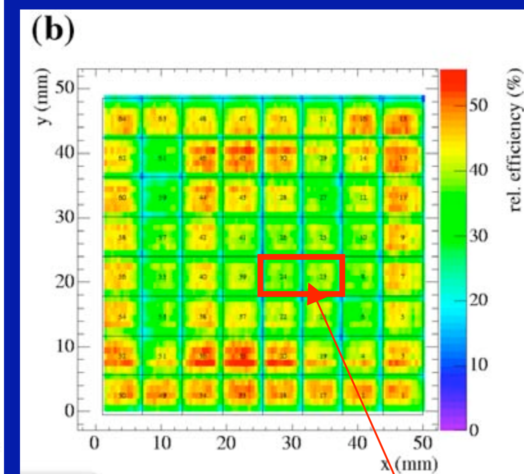
Ray tracing:



Geant 4 model:



H-8500 MaPMT:

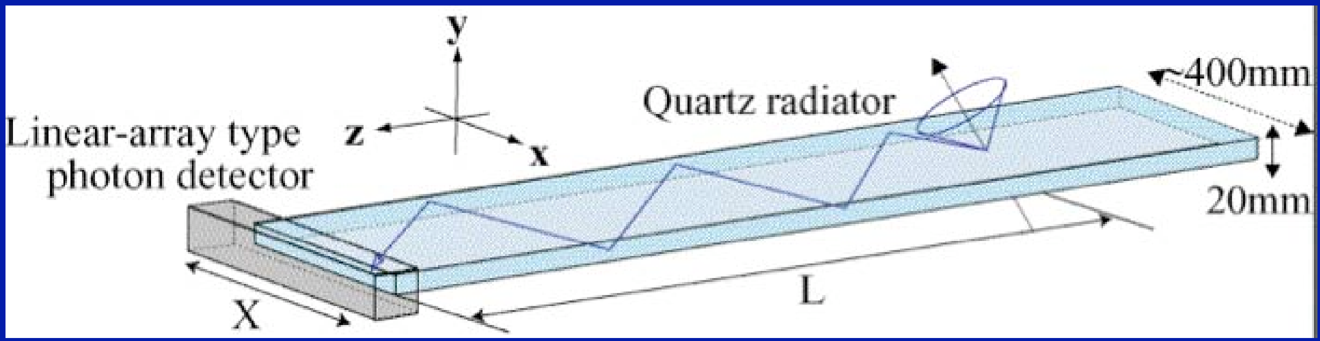


σ_{TTS} ~ 140ps

Double pixel

TOP at Belle II

K. Inami, RICH 2010, Cassis, France



- **Initial design used a measurement of x & time only, where time was measured to ~40ps. Later designs added a small expansion detector volume with more detector pixels, UV filters and a mirror segmentation.**
- **If the timing performance will be worse than proposed, this detector will not work that well.**
- **Its 3D segmentation is much worse than that of the FDIRC detector, and therefore there is more sensitivity to background.**
- **TOP counter people do not quote a θ_c resolution. This is because it is not very good by itself. One has to combine it with TOF in the likelihood analysis.**

TOP counter: measuring x & TOP only

B. Ratcliff, ICFA Inst. Bulletin, http://www.slac.stanford.edu/pubs/icfa/spring01/paper2/paper2a.html, 2001

For $\theta_{dip} = 90^o$:

$$TOP = L_{path} / v_g = L_{path}\, n_g / c = L_{bar}\, n_g / (k_z\, c)$$

$$\tan \alpha_x = k_x / k_z$$

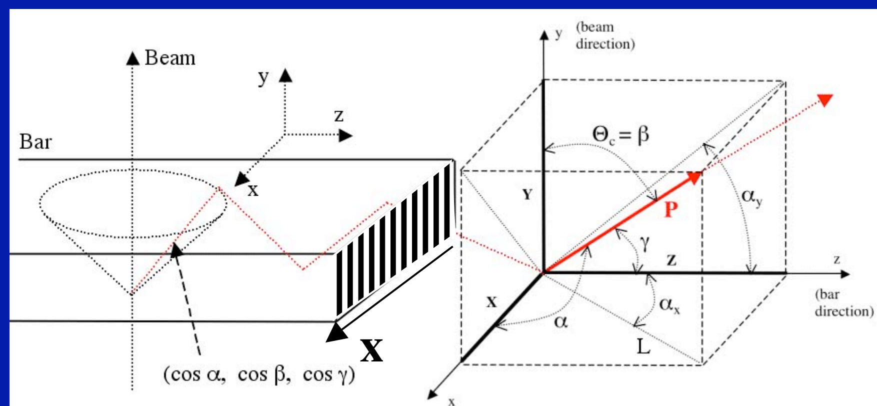
$$\sin \theta_c = k_z * \sqrt{(\tan^2 \alpha_x + 1)}$$

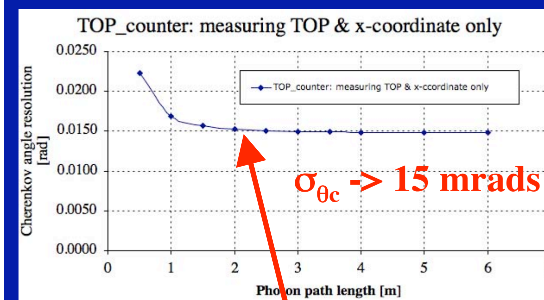
$$k_x = \sin \phi_c \sin \theta_c$$

$$k_y = \cos \theta_c$$

$$k_z = \cos \phi_c \sin \theta_c$$

Imaging with x & TOP:





$$\boxed{\sigma^2_{\theta c} \sim \tan^2 \theta_c \left[(\sigma(n_g)/n_g)^2 + (\sigma(TOP)/TOP)^2 + \sigma^2(\alpha_x) \tan^2 \alpha_x\right]}$$

- **Is measuring TOP & α_x sufficient ?**
- Putting numbers into the above equation: L_{path} = 2 m, σ_{TTS} ~ 40 ps, $\sigma(n_g)/n_g$ ~ 0.013 for Bialkali photocathode (see lecture I), σ(TOP)/TOP ~ 0.0039, and $\sigma(\alpha_x)$ ~ 0.005, one obtains $\sigma_{\theta c}$ ~ 15 mrads for Lpath > 1.5 meters.
- **<u>This is not good enough.</u> Therefore, proponents suggested: (a) use red-sensitive photocathodes, such as GaAsP, to reduce the chromatic error, (b) a UV filter to cut off low wavelengths, (c) add a mirror segmentation, which is a "cheap way" to do the y-pixillization (measurement of α_y), and (d) use the counter as a TOF counter to separate the particles.**

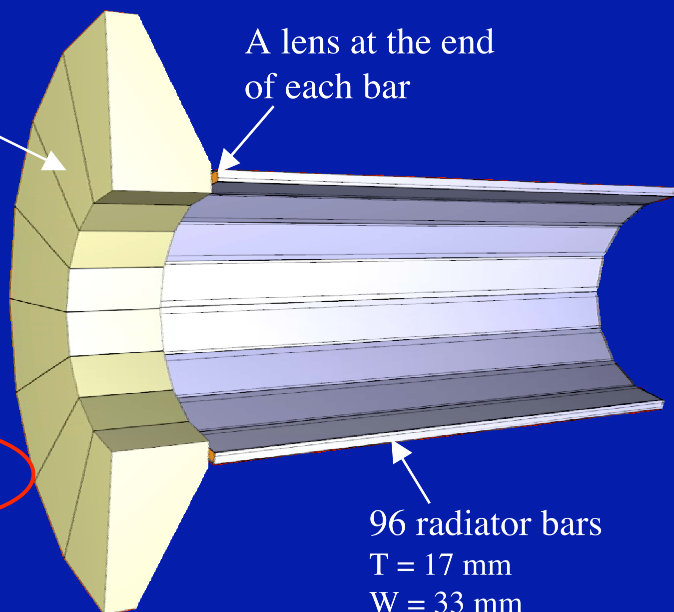
PANDA DIRC-like detectors

C. Schwarz, RICH 2010, Cassis, France

PANDA Barrel DIRC

Oil-filled expansion volume

A lens at the end of each bar

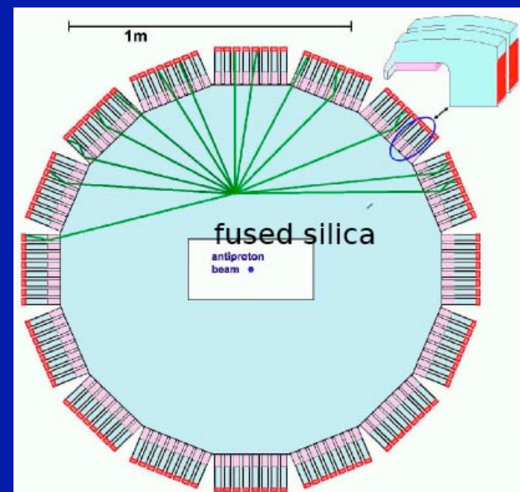


B = 20 kG

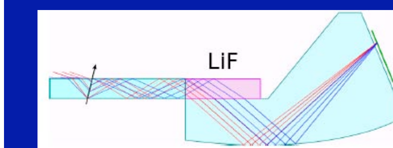
96 radiator bars
T = 17 mm
W = 33 mm
L = 2500 mm

PANDA endcap RICH:

Front view:



Hardware dispersion correction:



- **PANDA Barrel DIRC is similar to what we want to do with FDIRC for SuperB. They have advantage that they can start from scratch, we had to marry the optics to the existing bar boxes. Oil may create problems.**
- **The chromatic correction is made in hardware for endcap RICH.**
- **This is to be compared to FDIRC, where we plan to do this correction by timing (red photons go faster than blue photons).**

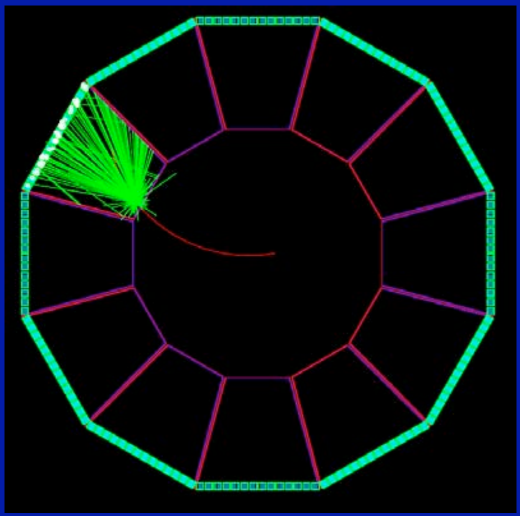
SuperB DIRC-like TOF

J.Va'vra, "Forward TOF for SuperB", http://agenda.infn.it/conferenceDisplay.py?confId=1161, Perugia, June 2009
L. Burmistrov, N. Arnaud, O. Bezshyyko, H. Dolinskaya, A.Perez, A. Stocchi, and J.Va'vra, SuperB R&D

$$\sigma_{Total} \sim \sqrt{\,[\sigma^2_{Electronics} + (\sigma_{Chromatic} / \sqrt{(\varepsilon_{Geometrical\_loss} * N_{pe})})^2 + (\sigma_{TTS} / \sqrt{\varepsilon * N_{pe}})^2 + \sigma^2_{Track} + \sigma^2_{detector\ coupling\ to\ bar} + \sigma^2_{to}]}$$

$\sigma_{Electronics}$ - electronics contribution ~ 5-10 ps (waveform sampling digitizer WaveCatcher)
$\sigma_{Chromatic}$ - chromatic term = f (photon path length) ~ 10-25 **(Geant 4)**
σ_{TTS} - transit time spread ~ 35-40 ps
σ_{Track} - timing error due to track length L_{path} (poor tracking in the forward direction) ~ 5-20 ps **(Fast Sim)**
$\sigma_{detector\ coupling\ to\ bar}$ - timing error due to detector coupling to the bar ~ 1-20 ps **(Fast Sim)**
$\sigma_{t\,o}$ - start time dominated by the SuperB crossing bunch length ~ 15-20 ps

MC simulation:

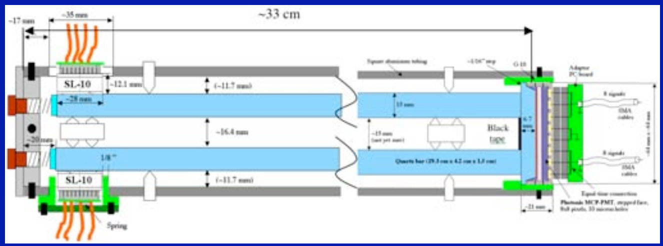


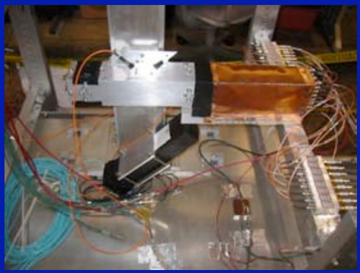
MC results:

- The total time resolution will be between 30-40 ps
- Npe > 5 photoelectrons at present, aiming for 10.

On-going test in the cosmic ray telescope (CRT):

- 16 channels equipped with the WaveCatcher electronics
- Start/stop provided by the MCP-PMT.



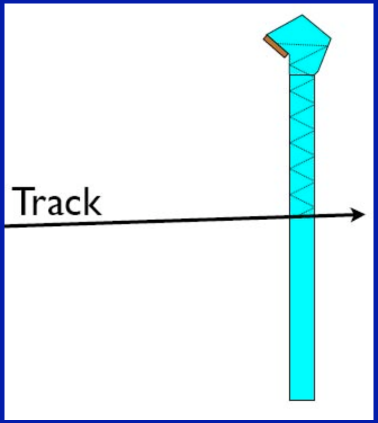


TORCH: DIRC-like detector

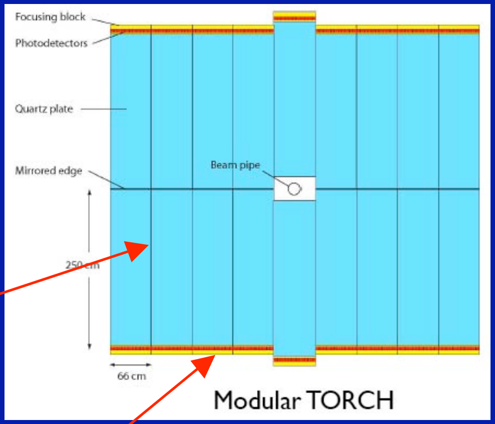
M. Charles and R. Forty, RICH 2010, Cassis, France

TORCH = TOF wall in LHCb

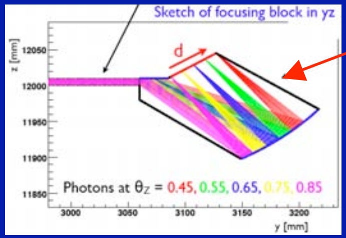
Side view:



Front view:



Quartz wall



Focusing block

T = 10 mm
W = 744 cm
L = 612 cm

- **TORCH is a novel rather challenging TOF detector for LHCb application.**
- **Simulation indicates a π/K separation up to ~ 8 GeV/c.**

Other RICH applications

T. Ypsilantis and J. Seguinot, Theory of RICH detectors, Nucl. Instr. & Meth. A343(1994)30-51

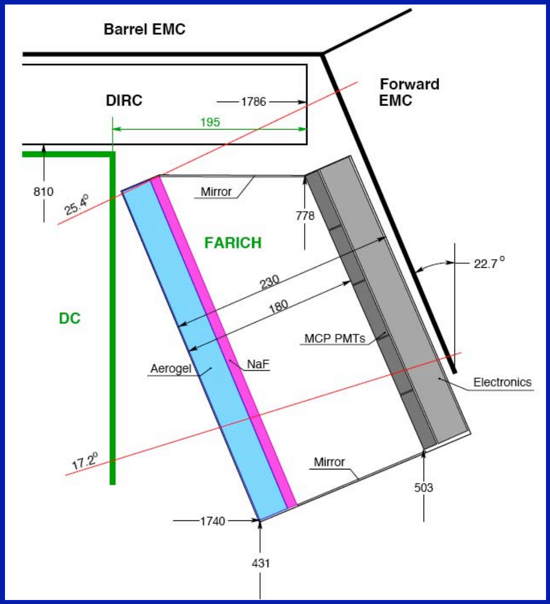
$$\theta_c = \arccos[1/(n\,\beta)] = \arccos(1/n * E/p) = \arccos[1/n * \sqrt{(p^2+m^2/p)}]$$

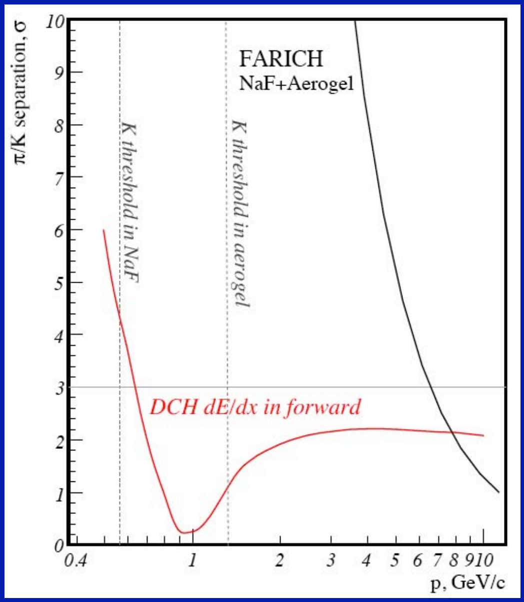
$m = p\sqrt{(n^2 \cos^2\theta_c - 1)}$ - RICH counters measure mass, if you know p & θ_c

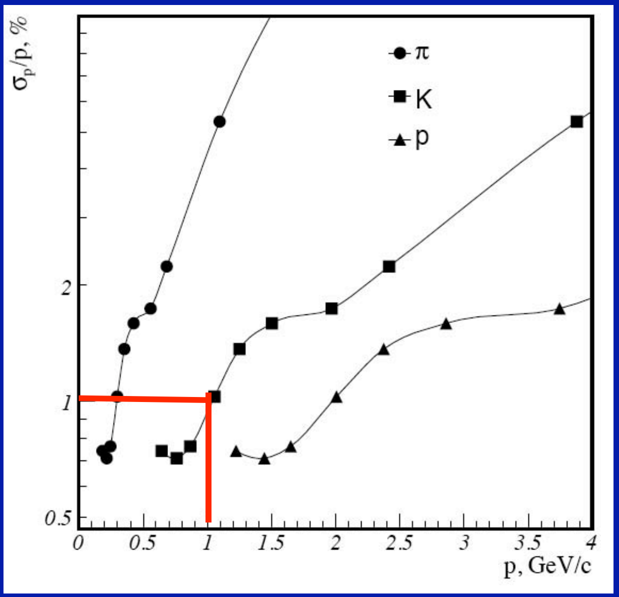
$\sigma_p/p = \gamma^2 * \sigma_\beta/\beta = \gamma^2 * \sigma_{\theta c}(tot) * tg\,\theta_c$ - fractional error in momentum p

=> RICH detector can measure a momentum !!

Kravchenko et al., Budker Inst., Novosibirsk, RICH 2010, Cassis, France:







Summary

- **The dE/dx "cluster counting" technique <u>might</u> be tried in a real experiment such as SuperB. It is, however, a significant challenge**.
- **TOF technique is progressing a lot thanks to new developments in (a) MRPCs, (b) MCP-PMTs and (c) G-APDs.**
- **However, larger scale applications of MCP-PMTs and G-APD arrays are limited by their present cost. One reason why the MRPC detectors have developed so quickly is that they are cheap and easy to make. We hear the news that the G-APD array price will come down significantly.**
- Therefore the new R&D program to develop MCP-PMTs at the U. of Chicago, Argonne Natl. lab, and Berkeley Space Science lab is a very important step. I hope it will bring the price down.
- I understand A. Brandt is also pushing another avenue to develop MCP-PMTs with Photonis & Arradiance. The approval is pending, I understand.
- **DIRC-like detectors are blooming.**